

Update on SM Higgs Cross Sections

EF01 Working Group Meeting

John Campbell, for the LHC Higgs WG1

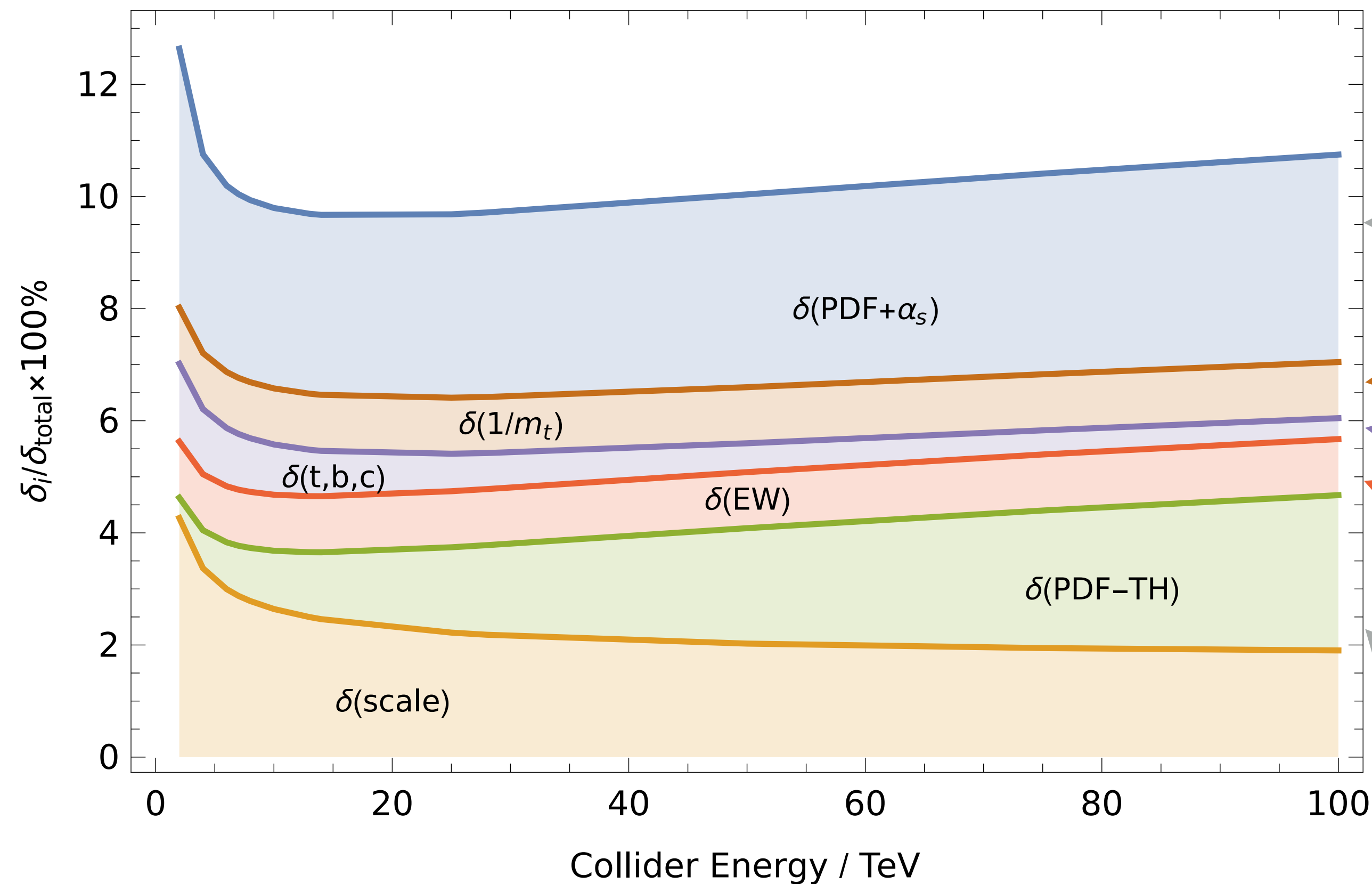
LHC Higgs WG1

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG1>

- Focus on SM Higgs cross-sections and branching ratios, and modeling of main backgrounds for cross-section measurements
 - include most precise theoretical predictions *and* reliable uncertainties.
- One subgroup per main production mode (ggF, VBF, VH, ttH) and one dedicated to off-shell cross-section and interference with backgrounds.
- Subgroup for branching ratios recently moved to ‘point-of-contact’ mode since level of understanding already exceeds current experimental needs.
- Cross-talk with other WGs on many topics— STXS, (SM)EFT, BSM Higgs, etc.
- Annual general meeting in December: <https://indico.cern.ch/event/1018653/>

Theory at work: ggF

Stephen Jones, LHCHWG, Dec 2021



Progress is steadily beating down sources of TH uncertainty

..... Needs data/more accurate determination

Removed

Czakon, Harlander, Klappert, Niggetiedt 21

Can be removed (?) similar techniques

Reduced from ~1% to 0.6%

Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20; + Bonetti, Panzer, Smirnov, Tancredi, Melnikov, ...

Missing $N^3\text{LO}$ PDFs

iHixs2: Dulat, Lazopoulos, Mistlberger 18

Highlights: ggF

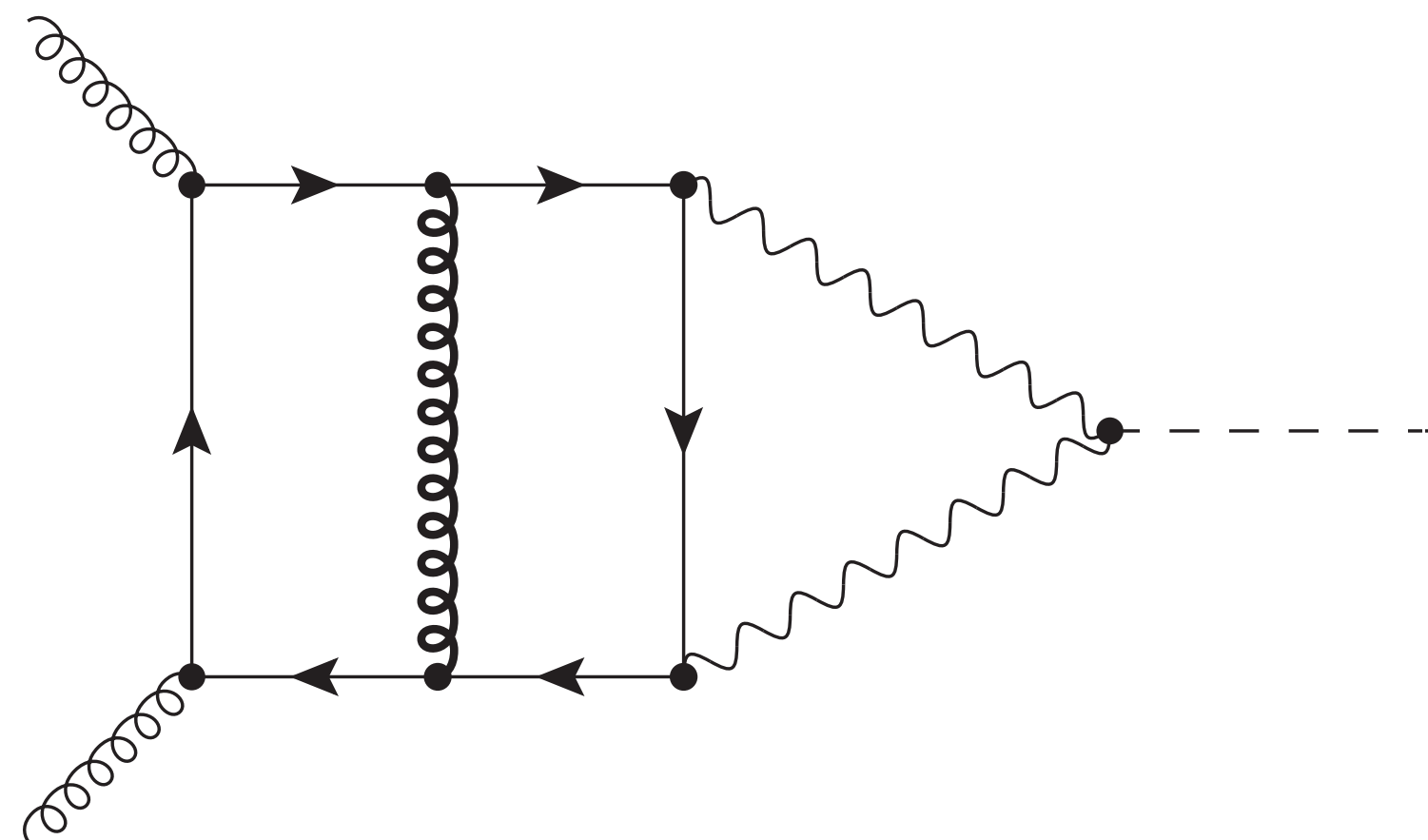
- Results beyond inclusive N³LO QCD

- fully differential

Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni 21

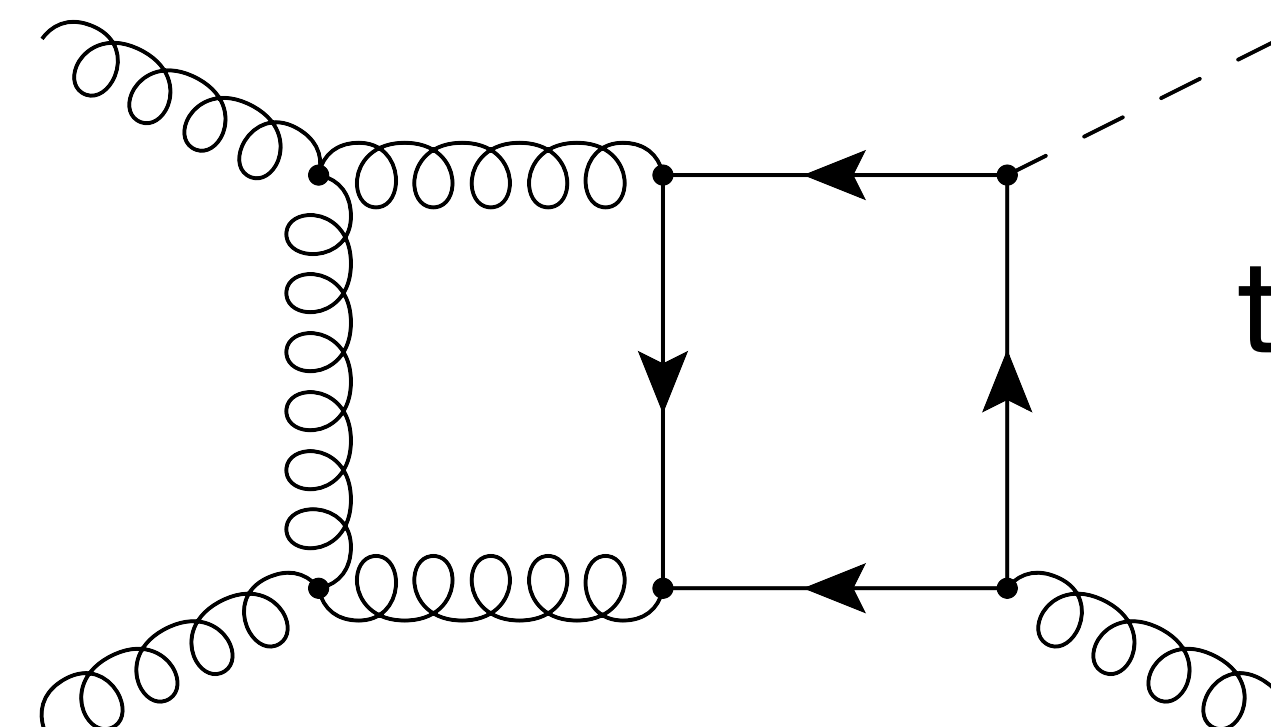
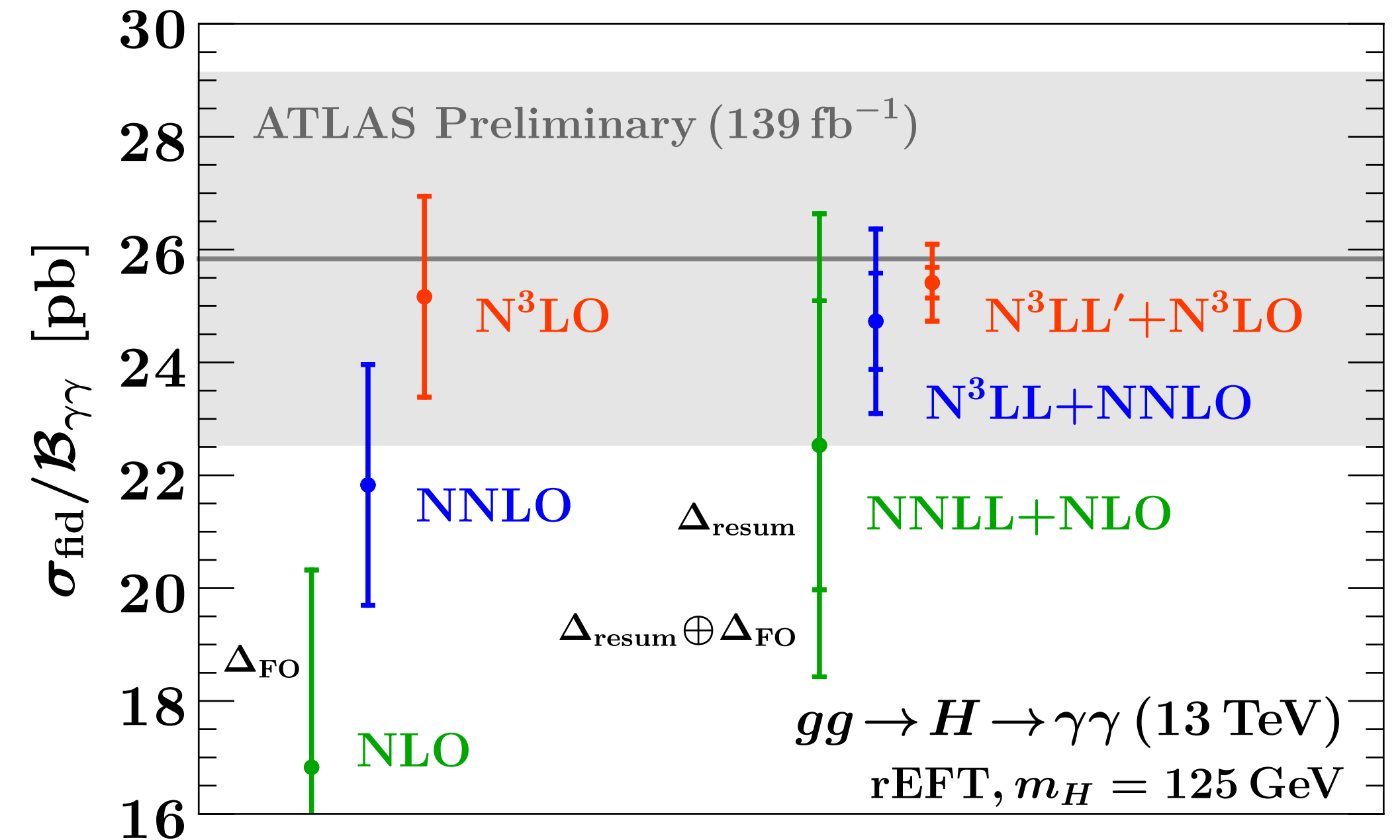
- including resummation at N³LL'

Billis, Dehnadi, Ebert, Michel, Tackmann 21



mixed QCD-EW corrections

Bechetti et al 20, Bonetti et al 20

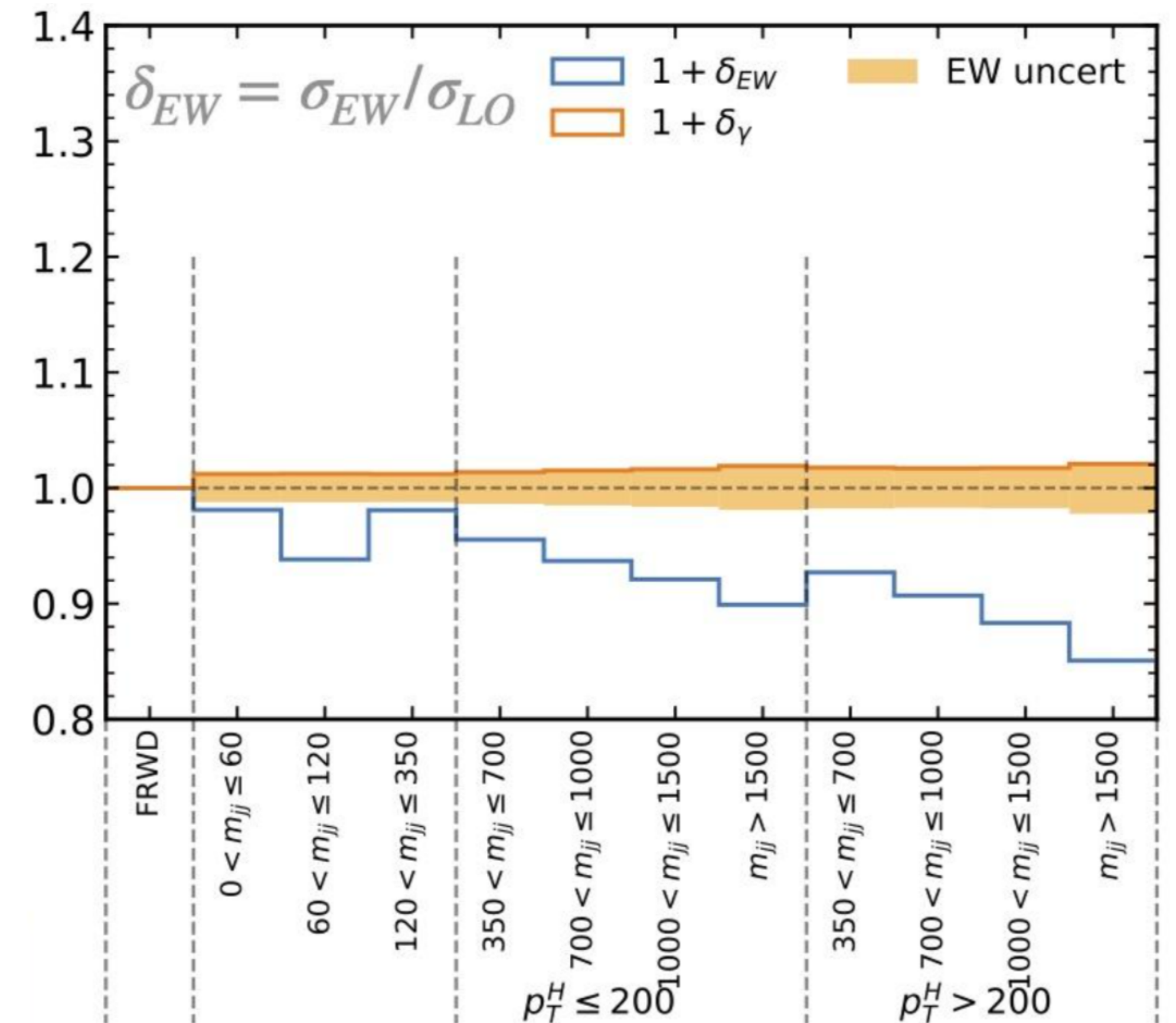


beyond HEFT,
top-mass effects
@ NNLO

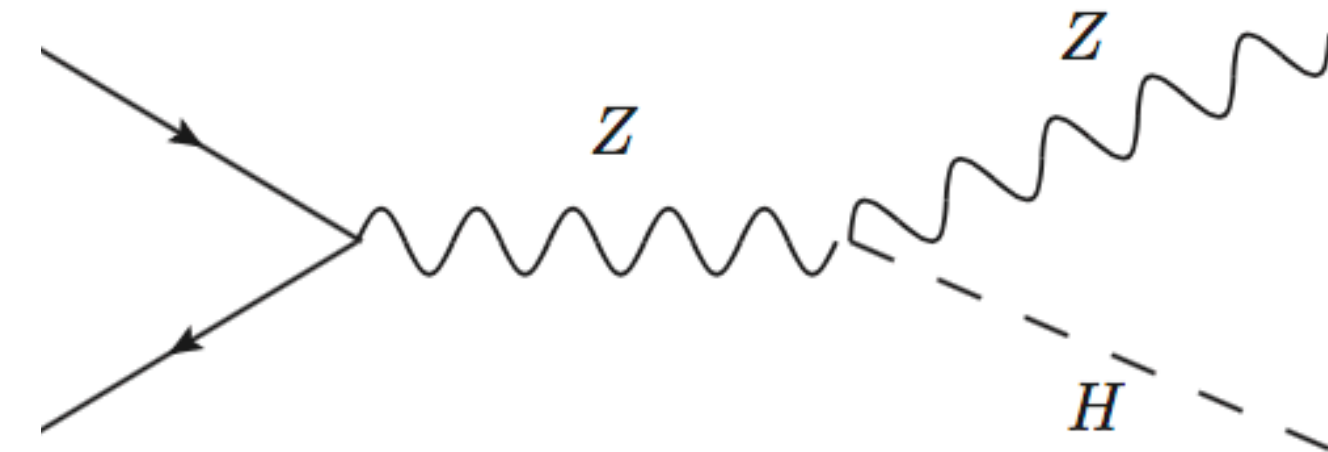
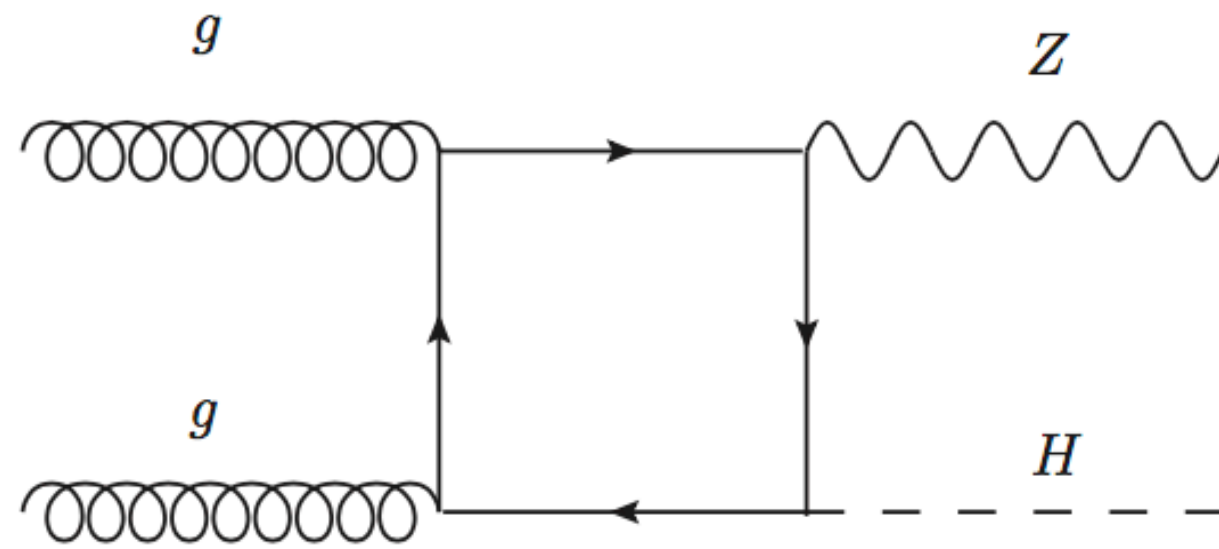
Czakon et al 21

EW effects: VBF

- Assessment of electroweak effects and uncertainties in simplified-template cross-section (“STXS”) bins
- NLO EW corrections result in two effects:
 - Sudakov-enhanced corrections
 $\sim \alpha \log^2 (Q/M)$, larger in signal-rich or boosted regions
 - channels with photon in initial state, recently under good control (LUXqed)



ZH: role of gg contributions



\sqrt{s} (TeV)	σ	+ δ (scale)	- δ (scale)	$\Delta_{\text{PDF}+\alpha_s}$
13	0.123 pb	24.9%	18.8%	$\pm 4.37\%$
14	0.145 pb	24.3%	19.6%	$\pm 7.47\%$
27	0.526 pb	25.3%	18.5%	$\pm 5.85\%$

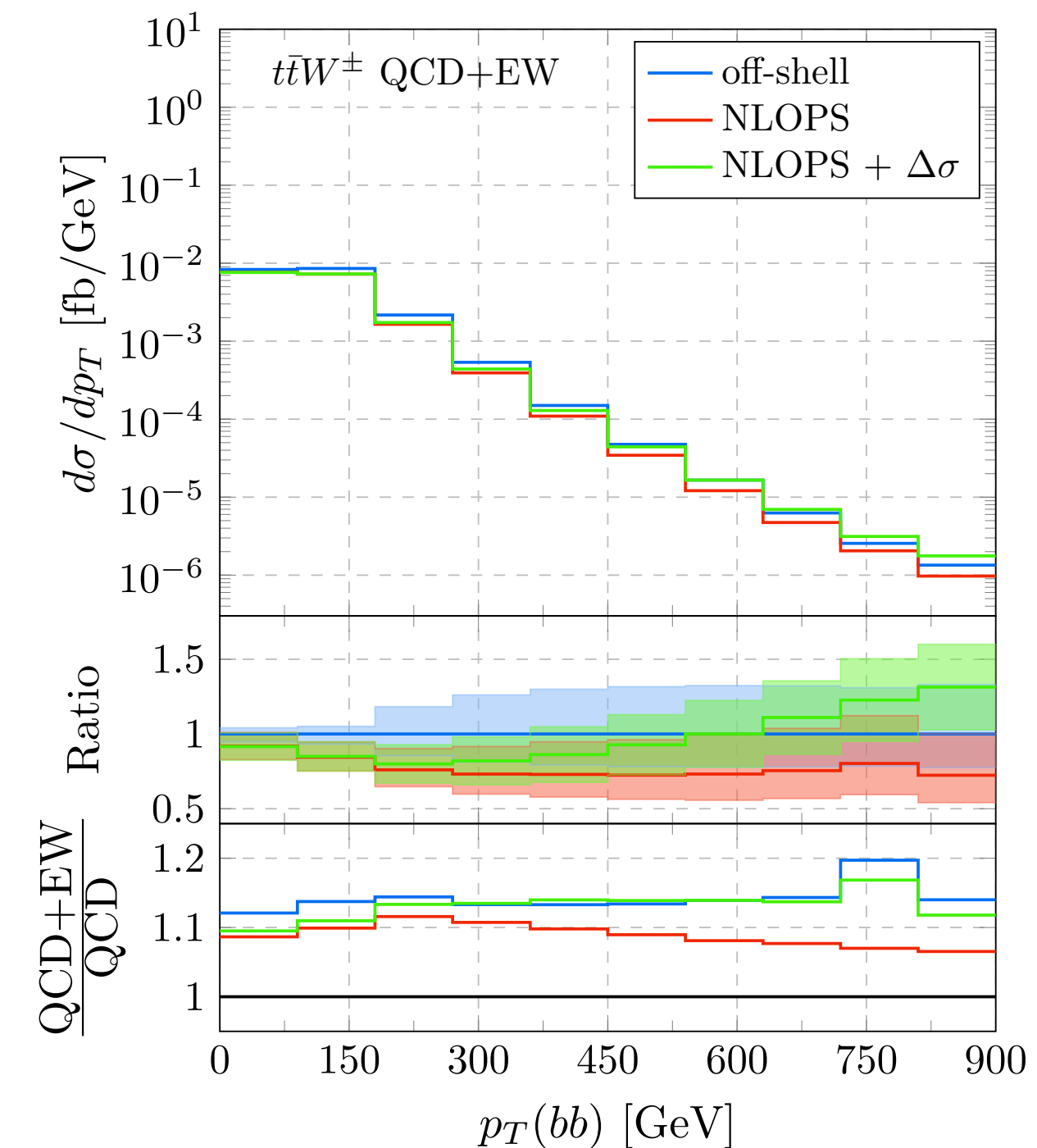
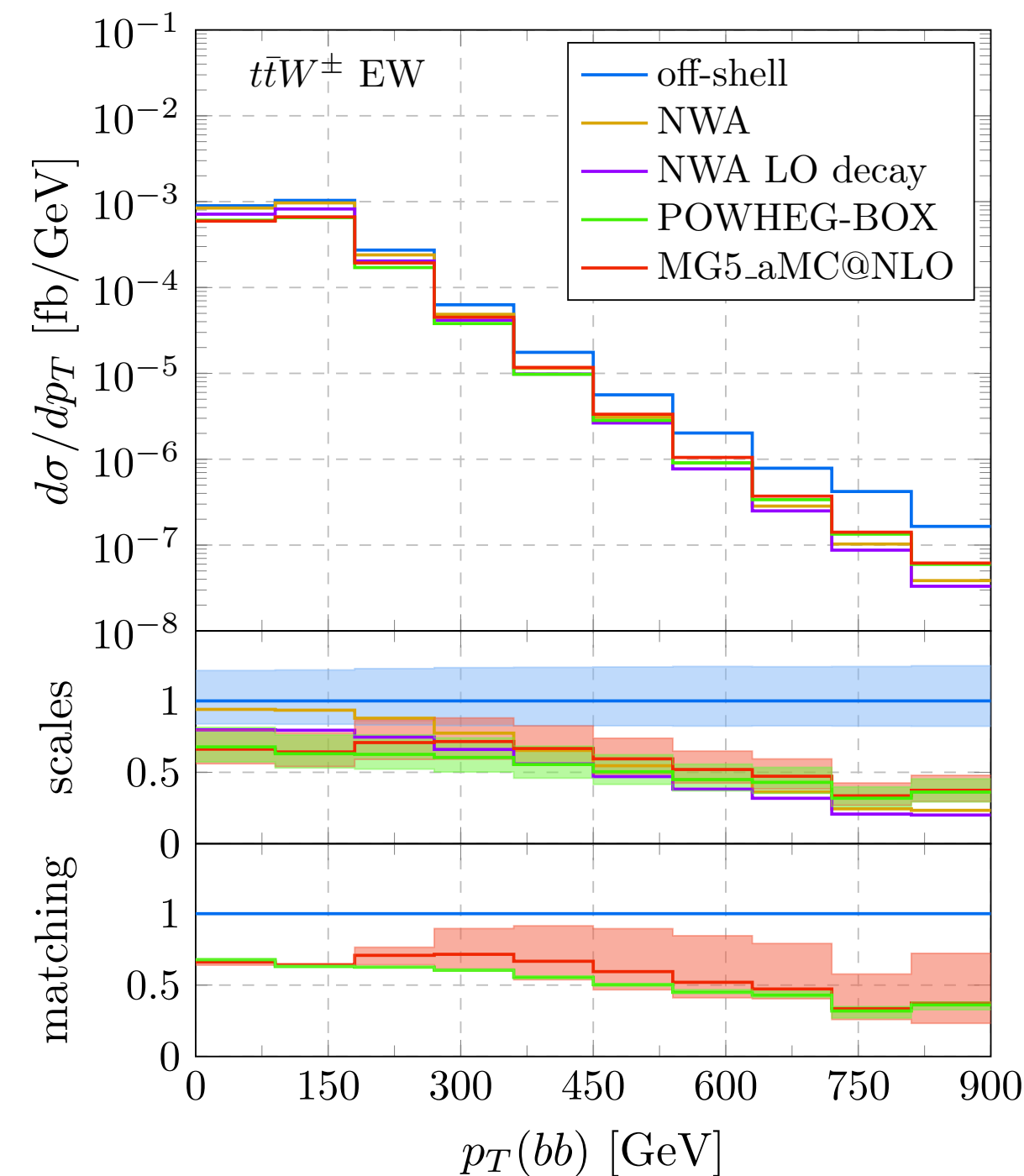
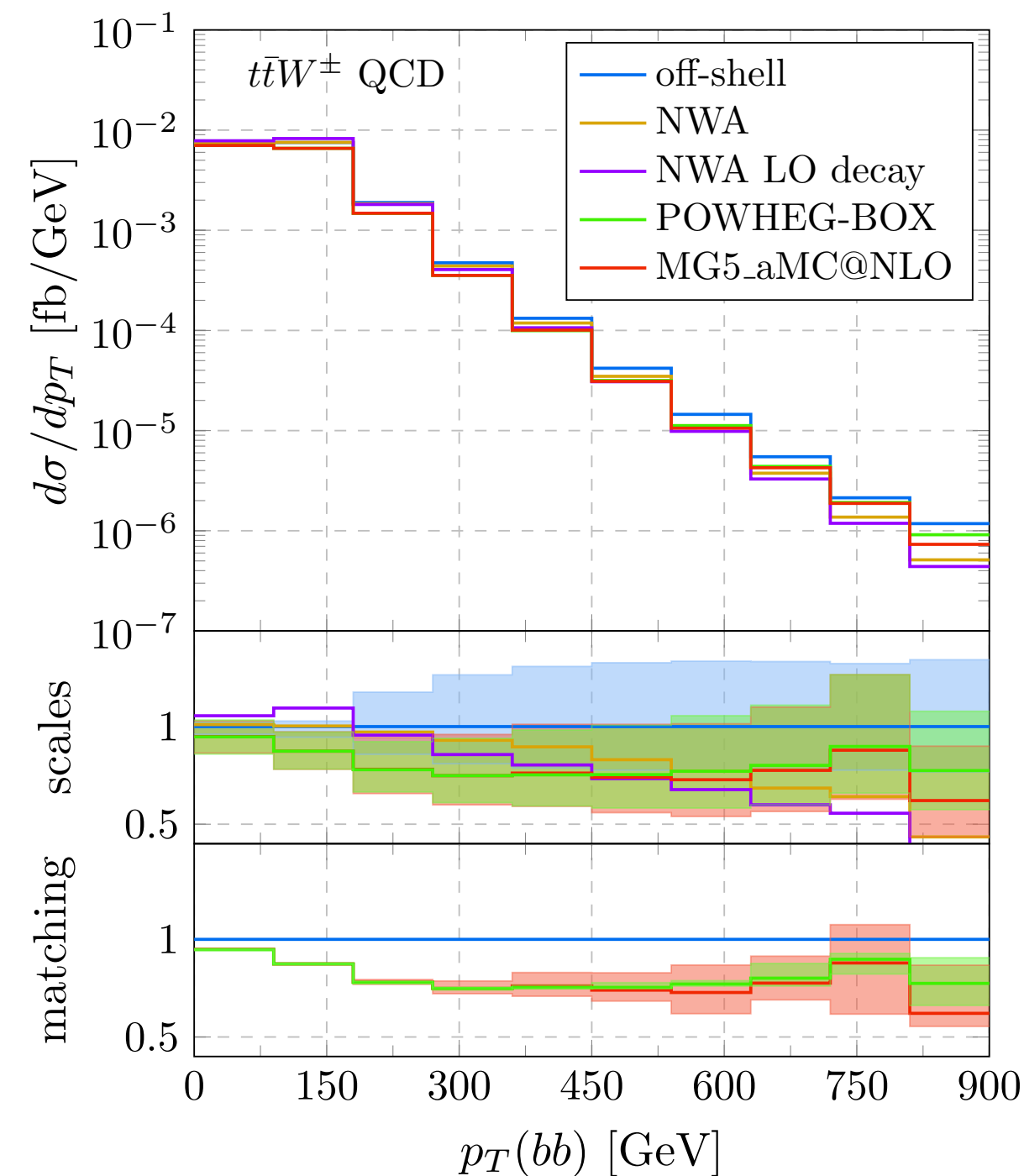
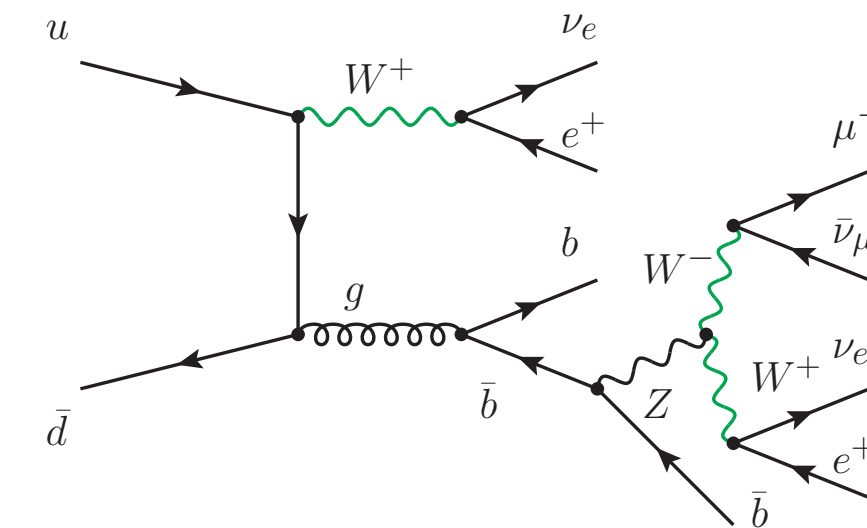
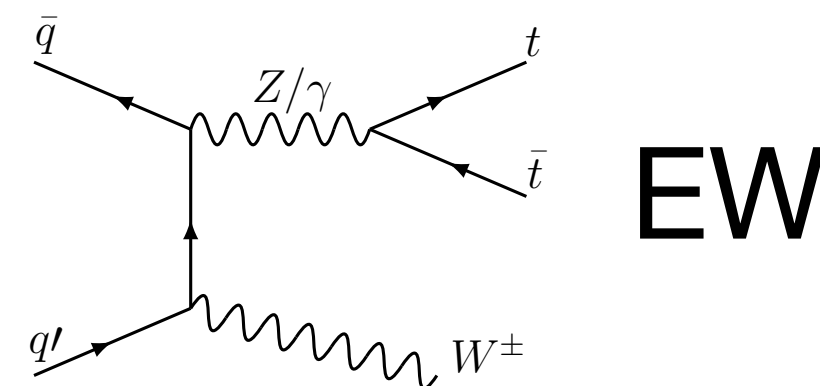
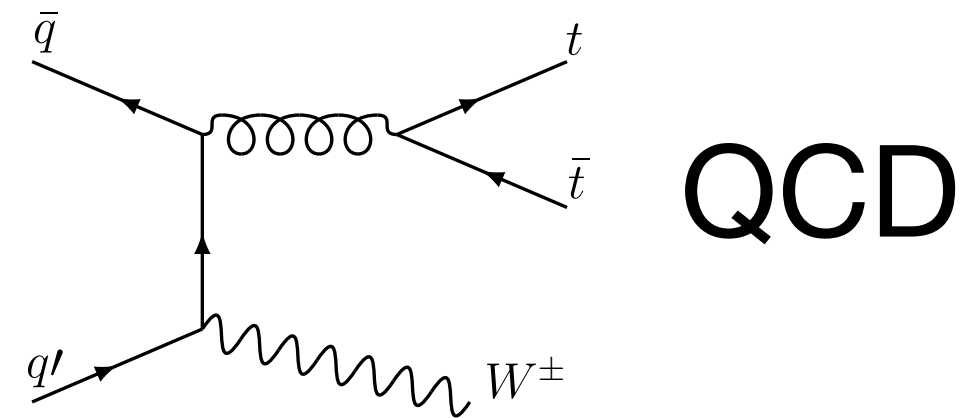
\sqrt{s} (TeV)	σ	+ δ (scale)	- δ (scale)	$\Delta_{\text{PDF}+\alpha_s}$
13	0.880 pb	3.50%	2.68%	$\pm 1.65\%$
14	0.981 pb	3.61%	2.94%	$\pm 1.90\%$
27	2.463 pb	5.42%	4.00%	$\pm 2.24\%$

- Enters for first time at NNLO, not well-captured by “precision” calculation at that order.
- Increased role at higher energies (small x) and in the boosted region; requires calculation of this contribution to higher order and jet-merging techniques
 - c.f. recent work demonstrating similar effects in NNLO calculation of VH+jet .

Gauld, Gehrmann-de Ridder, Glover, Huss, Majer 21

ttH: study of backgrounds

- Significant background to ttH (multileptons) from ttW process. Important to consider QCD and EW production, and off-shell effects.



“off-shell improved”
NLOPS

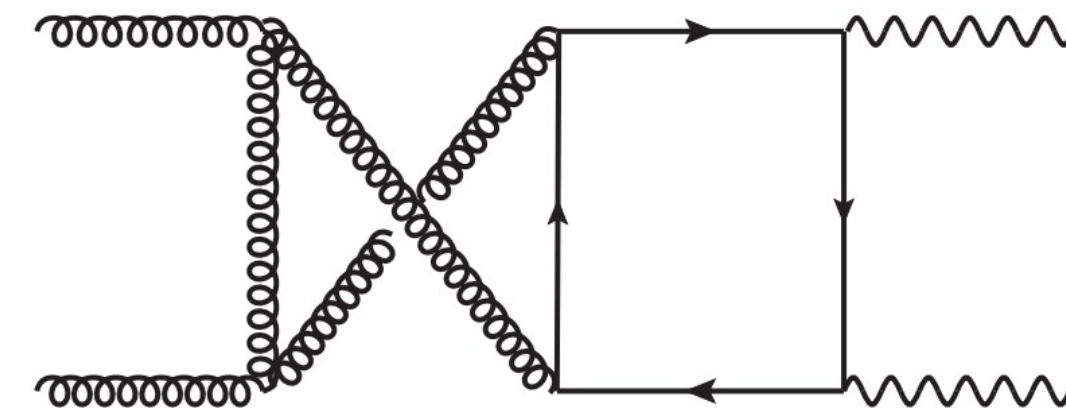
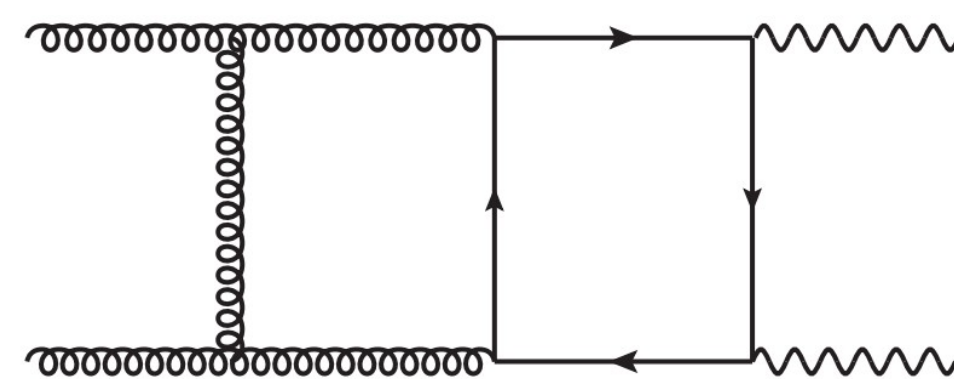
Bevilacqua, Bi,
Febres Cordero,
Hartanto, Kraus,
Nasufi, Reina,
Worek 21

Off-shell

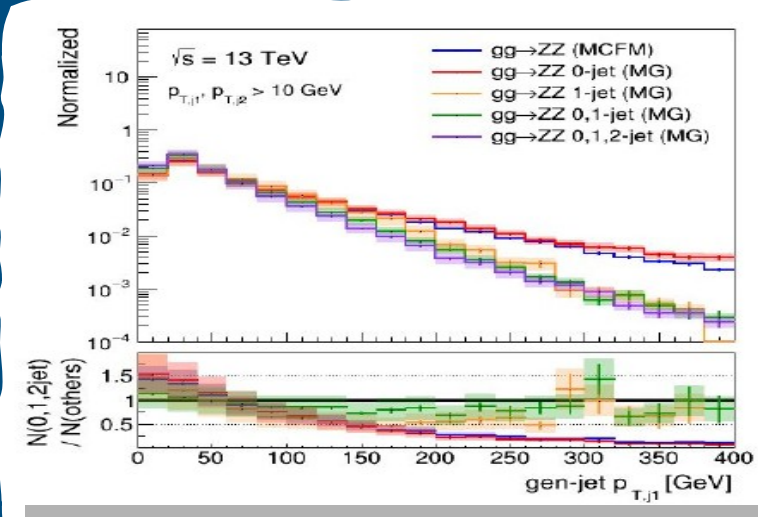
- Sizable contribution from off-shell Higgs boson
- inclusion of interference mandatory
- LO already a 1-loop $2 \rightarrow 2$ calc. (+ m_t non-zero)
- Very challenging problem even for jet-merging approach.

- Offshell predictions for $gg \rightarrow H \rightarrow VV$ require background $gg \rightarrow VV$ process to be taken into account.
 - Makes higher order corrections **very difficult to compute!**
- **Two-loop QCD amplitudes** for $gg \rightarrow ZZ$ and $gg \rightarrow WW$ including massive quark effects now known.

[Agarwal, Jones, von Manteuffel ('20); Brønnum-Hansen, Chen ('20,'21)]



- Substantial computing resources required: **still not used in cross section calculations...**



sub-process	core-hour
0-jet	0.085
1-jet	10.9
2-jet	15300



Massive increase in computational time for 2 jet emission!

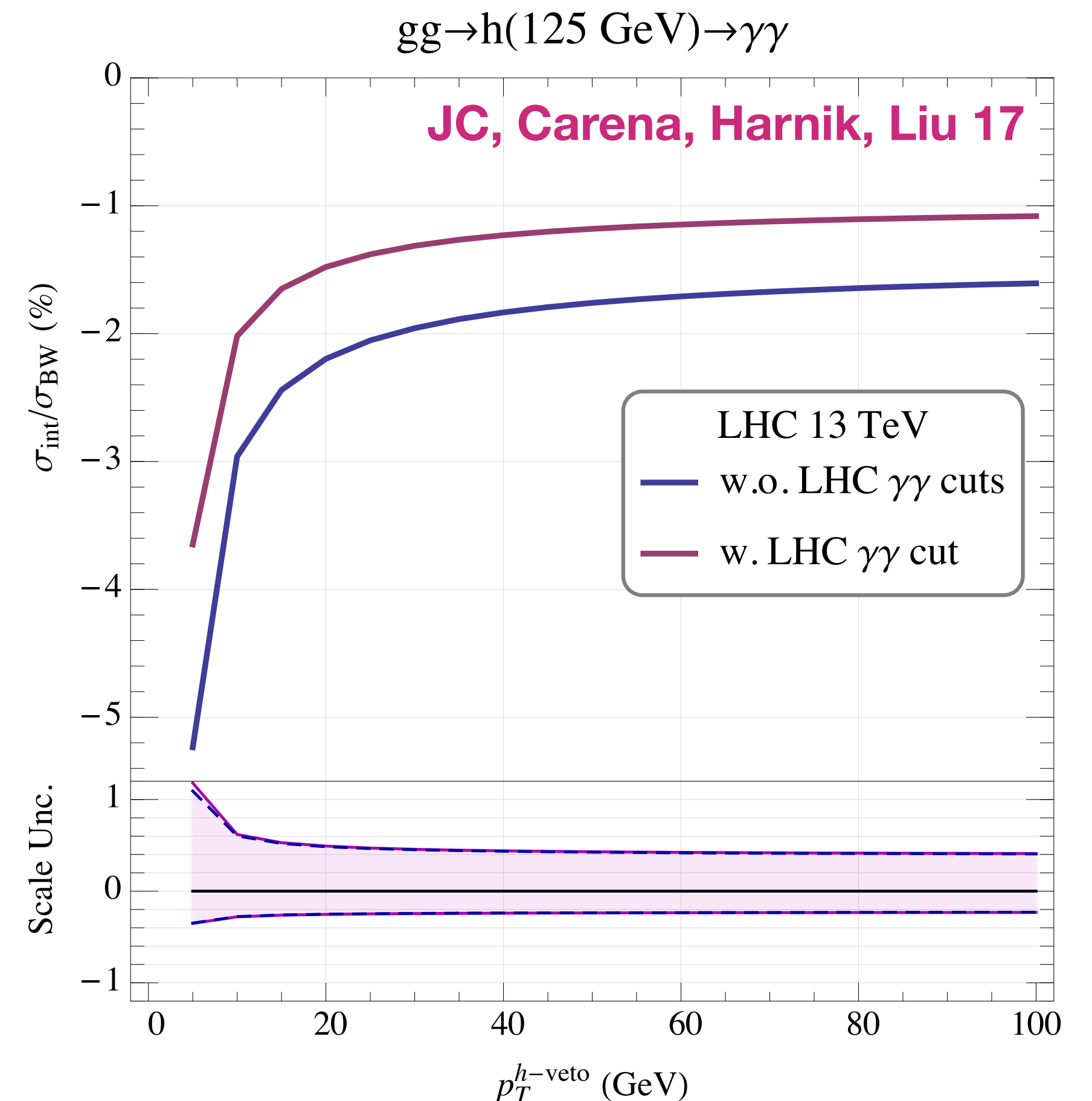
[Li et al. '20] [Talk by Congqiao Li]

**Nikolas Kauer,
LHCHWG,
Dec 2021**

On-shell interference

- Interference effects in the off-shell region important for unitarity, rather sensitive to modifications to Higgs width / other new physics
- Also gives rise to small changes in on-shell quantities.
- Well-known case: diphoton production. Gives rise to small shift in position of the mass peak, potential sensitivity to Higgs width.
Dicus, Willenbrock 88; Dixon, Siu 03; Martin 12; Dixon, Li 13
- Also results in percent-level change in the cross-section to which expts. will become sensitive
 - very tricky for theory — a 2-loop effect (so large uncertainty) and cut/jet veto-dependent — but recent progress at 3 loops.

Bargiela, Caola, von Manteuffel, Tancredi 21



WG1 plans

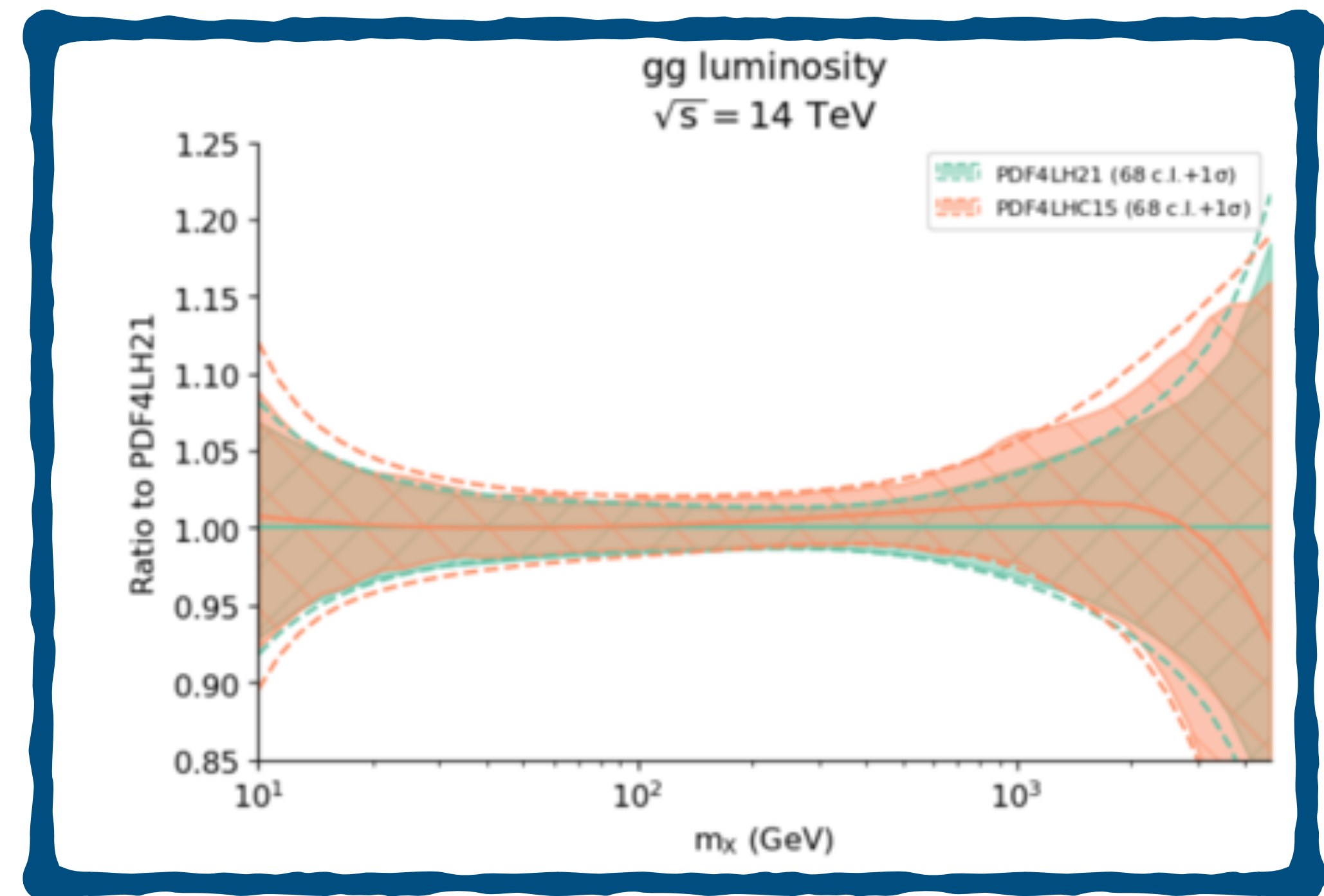
- Update recommended cross-sections with predictions for Run 3 @ 13.6 TeV.
- Simple to extrapolate from existing results (YR4/HL-HE exercise):

ggF (N3LO QCD + NLO EW)							
\sqrt{s} [TeV]	Cross Section [pb]	Uncertainty					
		Theory			PDF+ αs	PDF	αs
		pos [%]	neg [%]	Gauss [%]	[%]	[%]	[%]
13.6	52.144	4.6	-6.7	3.9	3.2	1.9	2.6
VBF (NNLO QCD + NLO EW)							
\sqrt{s} [TeV]	Cross Section [pb]	Uncertainty					
		Scale		PDF+ αs	PDF	αs	
		pos [%]	neg [%]	[%]	[%]	[%]	
13.6	4.0738	0.4	-0.3	2.1	2.1	0.5	

- Better (but more work): incorporate latest theory developments as well.

Cross-section update

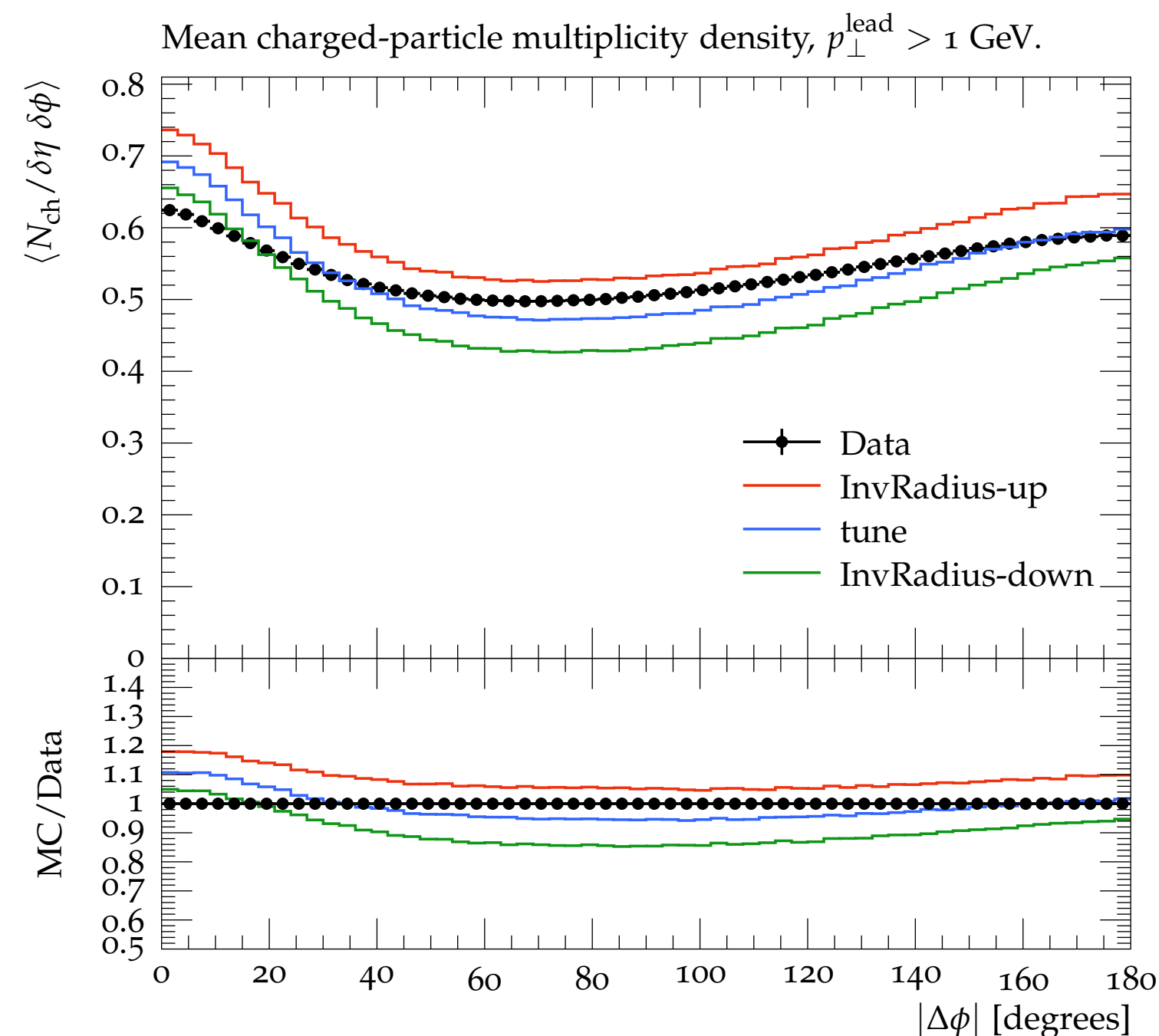
- New theoretical calculations, e.g. for gluon fusion: N³LO QCD (no threshold approx), exact mixed QCD-EW, top-mass effects.
 - small shifts in cross-sections and (perhaps reduced) uncertainties.
- New inputs: primarily PDFs.
 - photon PDF (EW uncertainties)
 - PDF4LHC21 update, if available.
- WG meeting beginning of Feb. to get the ball rolling; plan to document in a public note.



Robert Thorne, LHCHWG, Dec 2021

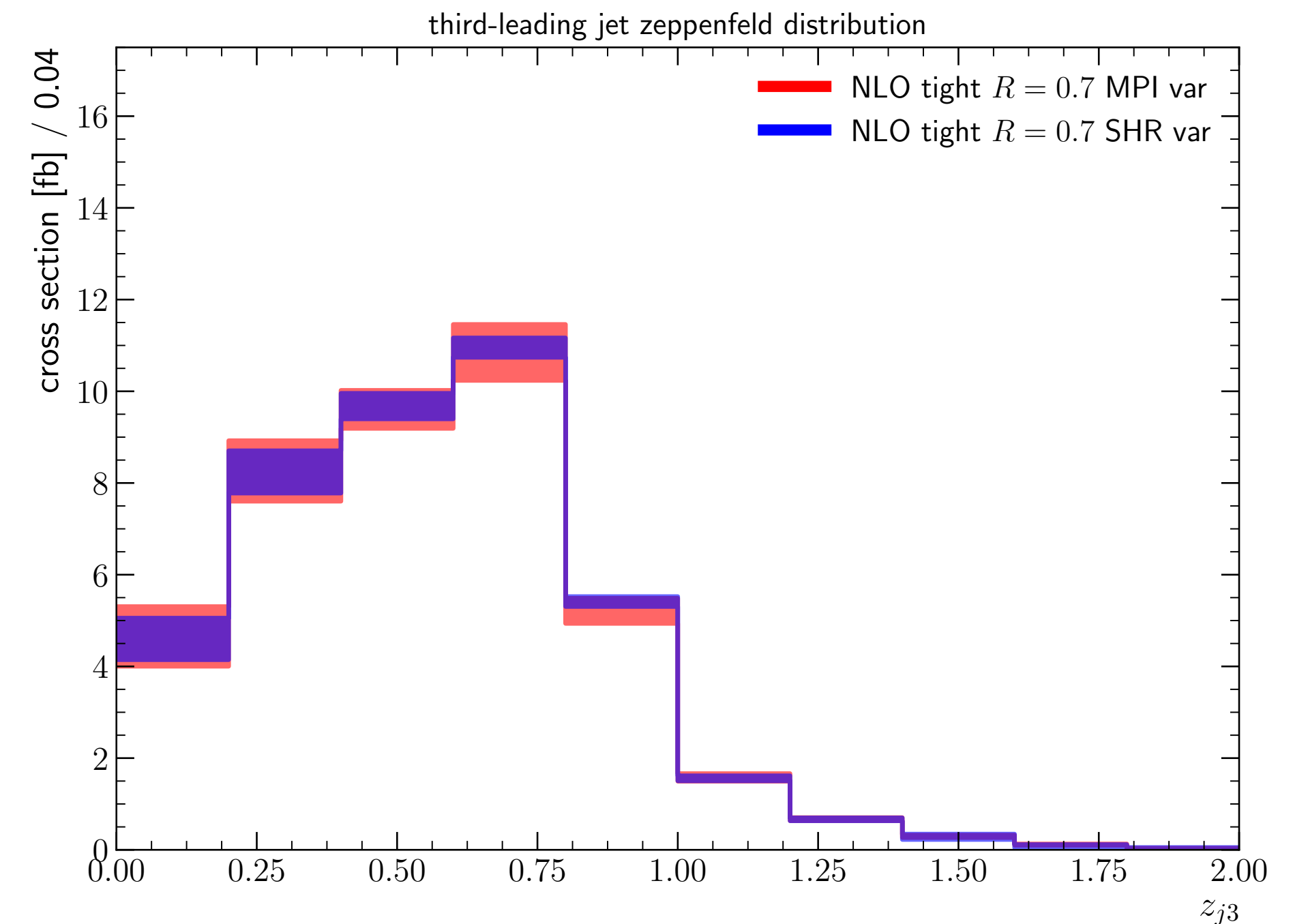
Parton shower uncertainties

- Understanding of parton showers now being scrutinized beyond usual “on-off” paradigm for estimating non-perturbative effects.
- Example: study of MPI effects in VBF/VBS scattering topologies (Z production). Tune HERWIG MPI and color reconnection models to 13 TeV underlying event data, propagate effect of $\sim 10\%$ variation. **Bittrich, Kirchgaesser, Papaefstathiou, Plaetzer, Todt 21**



→

**significant
(even leading)
uncertainties under
VBF/VBS cuts**



Parton shower studies

- Part of a larger recent effort, with many studies (especially VBF, ttH WGs), to assess compatibility of parton shower predictions and their uncertainties.
- Emphasize bottom-up approach where differences can be ascribed to physics choices in underlying models and/or degree of tuning.
- In addition, growing overlap and commonality between the subgroups, e.g.
 - changed hierarchy of production modes in boosted region
 - contamination of VBF and VH signals from gluon fusion + jets, multi jet matching and merging required to reach sufficient accuracy
- Plan for WG meeting in early spring to engage all subgroups and begin to document efforts, collate findings and recommendations.

Outlook

- The community continues to push Higgs predictions to new levels of precision, with LHC Higgs WG1 aiding optimal theory/data comparison.
- Most anticipated progress probably not by conventional advancing of perturbative orders for inclusive cross sections (except hopefully ttH).
 - *lifting approximations*: non-factorisable contributions (VBF), non-resonant and interference effects, mixed QCD-EW corrections, treatment of quark masses (ggF)
→ reduction and better quantification of uncertainties
 - *more differential*: higher orders across phase space (i.e. + jets) and inclusion in parton showers; better understanding of parton shower and event generator systematics; resummation effects
→ robust uncertainties in fiducial regions